



Review of biosolids management options and co-incineration of a biosolid-derived fuel

Murari Mohon Roy^{a,*}, Animesh Dutta^b, Kenny Corscadden^a, Peter Havard^a, Lucas Dickie^a

^a Nova Scotia Agricultural College, Canada

^b University of Guelph, Canada

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ABSTRACT

This paper reviews current biosolids management options, and identifies incineration as a promising technology. Incineration is attractive both for volume reduction and energy recovery. Reported emissions from the incineration of biosolids were compared to various regulations to identify the challenges and future direction of biosolids incineration research. Most of the gaseous and metal emissions were lower than existing regulations, or could be met by existing technologies. This paper also presents the results of an experimental study to investigate the potential use of biosolids for co-incineration with wood pellets in a conventional wood pellet stove. Pilot scale combustion tests revealed that co-incineration of 10% biosolids with 90% premium grade wood pellets resulted in successful combustion without any significant degradation of efficiency and emissions.

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1. Introduction

Sewage sludge refers to the solids separated during the treatment of municipal wastewater. According to United States Environmental Protection Agency (US EPA), biosolids refers to treated sewage sludge that meets the EPA pollutant and pathogen requirements for land application and surface disposal. Gomez et al. (2010) reported that the production of dry biosolids ranges from 20 to 32.85 kg per person per year. During the last couple of decades there has been a major changes regarding the disposal of sewage sludge. Prior to 1998, sewage sludge was primarily disposed into seawaters or was either used as a fertilizer on agricultural land, a common practice in Europe (Odegaard et al., 2002). An alternative was sludge incineration or simply landfilling. In 1998, European legislation Urban Waste Water Treatment Directive (UWWTD) was introduced that prohibited the disposal of sewage sludge into seawaters, in order to protect the marine environment. Present options for biosolids management in Europe, North America, Japan and many other countries consist of land application, landfilling (without or with energy recovery), composting, anaerobic digestion, heat-dried pellet fuel/fertilizer and incineration (without or with energy recovery). Land application, landfilling and incineration represented 80% of biosolids use in

the United States in 2004 (NEBRA, 2007). Land application for biosolids management in North America is still a low cost option. However, the practice of managing biosolids disposal through land application is increasing in both risk and complexity.

In Europe, landfilling was the main disposal method a decade ago. In 1999, 57% of municipal solid waste (MSW) was landfilled (67% in 1995) in Western Europe, and 83.7% in central and Eastern Europe (DHV CR, 2001). The recent scenario is different. Due to increasing greenhouse gas emissions (CH₄ and CO₂) and leaching of heavy metals to water and soil from landfilling, this option is becoming less attractive.

Due to stricter regulations concerning landfilling and land application it can be expected that there will be an increase in the role of incineration in the long term (Malerius and Werther, 2003). The technology of incineration in terms of process engineering, energy efficiency and compactness of plant has greatly improved. One of the major constraints in the widespread use of incineration is the public concern about possible harmful emissions. However, introducing new technologies for controlling gaseous emissions can minimize the adverse effects, while the reduction in the correspondent cost gives incineration considerable advantages in the future when compared to other available disposal routes. Modern fluidized bed incinerators have become a great potential for this application in comparison to the conventional multiple hearth type (Mininni et al., 1997).

This study reviewed different biosolids management options. Incineration was found to be an attractive and a prospective option for future biosolids management. Reported emissions from biosolids incineration are also compared to various regulations.

* Corresponding author. Address: Biomass Conversion and Biofuels, Department of Engineering, 39 Cox Road, Banting Building, Nova Scotia Agricultural College, P.O. Box 550, Truro, Nova Scotia, Canada B2N 5E3. Tel.: +1 902 893 6711; fax: +1 902 893 1859.

E-mail addresses: mroy@nsac.ca, mmroy5767@yahoo.com (M.M. Roy).

Furthermore, a combustion study of a biosolids with wood pellets in a conventional wood pellet stove was performed.

2. A short review on biosolids management options

The most common management options for biosolids are land application, landfill disposal and incineration. Land application is an attractive option for biosolids management (Peters and Rowley, 2009; Kim and Parker, 2008; Wang et al., 2008; Vasileski, 2007; Grant et al., 2006; Millner et al., 1998) as it is a cheap and easy solution with the added benefit that biosolids typically contain high concentrations of nitrogen, phosphorous and small quantities of other nutrients. However, land application has met much opposition in recent years for several reasons. Municipal biosolids are composed of waste streams from residential, commercial and industrial sources which raise the concern of potential chemicals, solvents and pharmaceuticals being included in the biosolids (Apedaile, 2001). Gibbs et al. (2007) and Rogers and Smith (2007) have shown that there are also concerns about the presence of pathogens (fecal coliforms, salmonellae) that can contaminate the land, concentrations of which have been found to increase over time even after destruction methods have been applied and samples indicate no measureable pathogens. Harrison and McBride (2009) indicated that high concentrations of heavy metals in biosolids are also of concern, as they can contaminate and reduce the productivity of land used for disposal by reducing the bacterial diversity within the soil (Moffett et al., 2003). In addition to the measureable factors mentioned, there is also a negative public perception to the practice in general (Harrison and McBride, 2009).

Landfilling is becoming a more costly disposal option for several reasons. The increasing population (and thus production of biosolids) requires new landfills to be created on valuable land near the source of generation or they must be transported long distances and changing regulations require new landfills to be highly engineered (Millner et al., 1998). Landfilling with energy recovery from landfill gas is a modern biosolids management option (Gomez et al., 2010). Disposal of incinerated ash in landfills may however shall be an attractive option in cases where ash contains a high concentrations of heavy metals (Wang et al., 2008; Kim and Parker, 2008; Vasileski, 2007; Grant et al., 2006).

Gomez et al. (2010) has shown that advanced thermochemical processes such as gasification and pyrolysis may be effective in emissions reductions and energy recovery, as well as resulting in a reduction in the total volume of material for final disposal. However, these are in the nascent stage of research. Thermal treatment is arguably one of the best options for biosolids management with many advantages (Sanchez et al., 2009; Ned et al., 2009; Jenkins et al., 1997). This option means thermal processes with possible energy recovery and a significant volume reduction. The limitations facing landfilling and recycling, and the ban on sea disposal lead to the expectation that the role of incineration will increase in the future. Sludge incineration offers a combination of several advantages not found in other treatment alternatives, including a large reduction of sludge volume to a small stabilized ash. In large urban areas where vast quantities of wastewater sludge is produced, lack of readily available disposal space, the need to minimize odor generation from landfill and aesthetic objections from nearby residents makes incineration an attractive sludge disposal method. Incineration as a competitive treatment option for biosolids management is reported in several recent studies (Cherubini et al., 2009; Houillon and Joliet, 2005; Lundin et al., 2004; Apedaile, 2001; Davis et al., 2007; Cartmell et al., 2006).

Cherubini et al. (2009) performed life cycle assessment to compare the environmental impact of incineration and the landfilling of municipal solid waste in São Paulo City, Brazil. Incineration with

energy recovery and landfilling treatment systems were assessed. Energy consumption, recovered resources and emissions to both air and water were quantified and analyzed in terms of their potential impact. Global warming, acidification and nutrient enrichment were assessed as environmental impact categories. Landfilling presented the highest environmental impact in the investigation, while incineration with ash disposal to a landfill site presented the lowest environmental burden regarding the impact categories assessed in this study. The results showed that a shift in waste treatment from landfilling to incineration would decrease the overall environmental impact while also allowing energy recovery.

A study by Houillon and Joliet (2005) quantified the environmental impact of six processes used for wastewater urban sludge treatment: agricultural land spreading of limed pasty sludge; specific incineration in fluidized bed of pasty sludge; wet oxidation of liquid sludge; pyrolysis of dried sludge; incineration in cement kilns of dried sludge; and landfill of limed pasty sludge. The study focused on energy and emissions contributing to global warming over the whole treatment life cycle. The energy balance suggests that incineration and agricultural spreading have the lowest non-renewable primary energy consumption. For global warming, incineration in cement kilns has the best balance, while landfill and agricultural spreading have the worst.

Lundin et al. (2004) have assessed the environmental and economic consequences of four recycling and disposal options for municipal sewage sludge. The four options were: agricultural application, co-incineration with waste, incineration combined with phosphorus recovery and fractionation including phosphorus recovery. Life cycle analysis was used to assess the environmental consequences. This study has shown that two sludge handling options, incineration and direct application on agricultural soil, have respectively economic and environmental restrictions. The economic assessment showed that agricultural application had the lowest cost of the options, however, transportation distance largely affects the cost of this option. In larger cities, where available land is limited and the quality of sludge is questionable, energy recovery is a better alternative. Alternatively, co-incineration had the best energy balance with the least emissions. The application of sludge on agricultural land was the least preferable option from an environmental perspective.

Apedaile (2001) presented a scenario of biosolids management options and their share in Canada. The share of different options was: incineration (47%), land application (43%), reclamation and other uses (6%) and landfill (4%). Incineration was suggested as a promising alternative to land application in another Canadian study performed by Davis et al. (2007). Dewatered biosolids are being successfully incinerated in a number of plants in different countries in full compliance with current air emission requirements. Davis et al. (2007) indicated that techniques are available to meet even more stringent air emission requirements that may be put in place in the future. Energy recovery in the form of heat or electricity is possible and practiced to varying degrees depending on the economic case. In Germany, for example, electrical power produced as part of an energy recovery ('Green') system commands a higher sale price from utilities than 'conventional' power, which makes co-generation using biosolids as the energy source more attractive. High electricity rates in Europe however provide a much more attractive economic case when compared to North America for cogeneration.

An integrated appraisal of five technology scenarios for the co-combustion of biosolids in the UK energy and waste management policy context is presented by Cartmell et al. (2006). The scenarios were: (i) Scenario 1, co-combustion with coal in a third party large scale combustion facility with no participation of the water utility in power generation or sale. (ii) Scenario 2, co-combustion with wastes at a third party energy-from-waste (EfW)

facility. (iii) Scenario 3, co-combustion with wastes at an EfW facility operated by the water utility. (iv) Scenario 4, co-combustion with supplementary fuel (plant biomass) at a water utility combustion facility with possible third party involvement. (v) Scenario 5, co-combustion in a cement kiln or other industrial user of power and/or heat (CHP). All scenarios provided a net energy gain (0.58–5.0 kW h/kg dry solids), having accounted for the energy required for transportation and sludge drying. Scenario 1 was found a cost-effective economically feasible option for biosolids management. Country such as Hong Kong, which has no agricultural or forestry lands suitable for biosolids disposal, prefers incineration as the best option for biosolids management (Lowe, 1993).

It has been shown from this review that thermal processing of biosolids; especially incineration will play an important role for biosolids management. Several technologies currently exist for co-combustion of biosolids in which high combustion efficiencies are achievable. With modern and effective flue gas cleaning technologies currently available in incineration plants, the combustion of biosolids can meet strict emission limits. Co-combustion of biosolids with coal is found a cost-effective option (Cartmell et al., 2006). As wood pellets are costlier than biosolids, a partial substitution of wood pellets by biosolids would be cost-effective. The next section of this paper compares reported emissions from the incineration of biosolids to various regulations.

3. Regulations related to biosolids and incineration

3.1. Metals in biosolids

The US EPA has set a regulation to protect human health and the environment from biosolids. Table 1 shows the maximum allowable concentrations of metals in biosolids (40 Code of Federal Regulations (CFR), Table 3 of § 503.13. – Pollutant Concentrations). Mercury, selenium, cadmium and arsenic have the lowest allowable concentrations: 17, 36, 39 and 41 mg/kg (db), respectively, whereas zinc, copper, chromium and nickel have the highest allowable concentrations: 2800, 1500, 1200 and 420 mg/kg (db), respectively. These limits apply to land application.

3.2. Air pollutant emissions standard

The emissions from biosolid combustion release pollutants to the air. Table 2 shows US EPA waste incinerator emission standards. USEPA's 40 CFR Part 503 Rule regulates the emission of metals and total hydrocarbons and or carbon monoxide from biosolids incinerators (40 CFR, Table 1 of § 503.43. – Pollutant limits).

The majority of ash generated by the incineration of biosolids is disposed of in either municipal solid waste landfills or ash mono-fills. Any ash that meets the definition of a hazardous waste must comply with regulations defined in 40 CFR Parts 261 and 268. Table 3 shows US EPA regulated limits by toxicity characteristic

Table 2

US EPA waste incinerator air pollutant emissions standard (US EPA, 1993).

Pollutant	Unit	Concentration
Arsenic (As)	($\mu\text{g}/\text{Nm}^3$)	0.023
Cadmium (Cd)	($\mu\text{g}/\text{Nm}^3$)	0.057
Nickel (Ni)	($\mu\text{g}/\text{Nm}^3$)	2.0
Chromium (Cr)	($\mu\text{g}/\text{Nm}^3$)	0.65 ^a
Beryllium (Be)	g	≤10 g during any 24 h period
Mercury (Hg)	g	≤3200 g during any 24 h period
Carbon monoxide (CO)	ppm	100 ^b
Total hydrocarbon (THC)	ppm	100 ^b

^a Type of incinerator – fluidized bed with wet scrubber.

^b Values corrected to 0% moisture and 7% O₂.

leaching procedure (TCLP) for heavy metals in the leachate of hazardous waste which is also applied for incinerator bottom ash.

3.3. Air pollution control system from biosolids incineration

A review of the pollutants in sewage sludge has been carried out by Eriksson et al. (2008). Of the 192 compounds found to be present, 99 were identified as being hazardous of which poly aromatic hydrocarbons (PAH), dioxins and furans, pesticides, endocrine disruptors and aliphatic hydrocarbons were considered to be significant. Based on the composition of sewage sludge presented in EC-Research Project, APAS-contract COAL-92-0002 by Abbas et al. (1995), incineration of sludge may be seen as a potential source of various pollutants and care must be taken during its disposal. Inadequate care during the disposal of waste has caused various types of environmental damage including pollution of ground water, contamination of soil and surface water, pollution of air, and poisoning of humans and animals either through direct contact or through the food chains. Of great concern to the public are the following possible pollutants from sewage sludge incineration:

1. Heavy metals.
2. Bottom and fly ash.
3. Dioxins and furans, NO_x, N₂O, SO₂, as well as HCl, HF and C_xH_y.

A study by Park et al. (2009) reviewed the characteristics of PAH, which is a group of pollutants found in flue gas during incineration of sewage sludge. On-site examinations were conducted on five sludge incineration facilities in Korea to better understand the emission characteristics of PAH from the facilities. Total PAH was reported at only 0.6–8% of allowable levels. Airborne particulate matter (PM) is an important environmental issue because of its association with acute respiratory distress in humans. Fernandez et al. (2002) reported results from collaborative interdisciplinary research on the inhalation health risks caused by particles emitted from co-combustion of municipal sewage sludge (MSS) and coal. The most practical outcome of this work is that it suggests care must be taken to evaluate the use of biomass, in particular MSS,

Table 1

Maximum allowable metal concentration in biosolids (US EPA, 1993).

Pollutant	Allowable concentration (mg/kg monthly average, db)
Arsenic (As)	41
Cadmium (Cd)	39
Chromium (Cr)	1200
Copper (Cu)	1500
Lead (Pb)	300
Mercury (Hg)	17
Molybdenum (Mo)	18
Nickel (Ni)	420
Selenium (Se)	36
Zinc (Zn)	2800

Table 3

TCLP limits for heavy metals in the leachate of hazardous waste (US EPA 40 CFR, 2007).

Hazardous metal species	Regulatory TCLP limit (mg/L)
Arsenic (As)	5
Cadmium (Cd)	1
Chromium (Cr)	5
Copper (Cu)	–
Mercury (Hg)	0.2
Lead (Pb)	5
Selenium (Se)	1
Zinc (Zn)	–

Table 4
Rates of N₂O emissions from different types of combusted biosolids (Ned et al., 2009).

Country	Biosolids	g N ₂ O/tonne biosolids	Weight basis
Japan	Dehydrated	900	Wet weight
	Lime sludge	294	Wet weight
	Cake	1520–6400	Dry weight
Germany	Cake	990	Dry weight
Montreal (preliminary data, 2008)	Cake	1000–5000	Dry weight
IPCC default	–	990	Dry weight
IPCC default	–	900	Wet weight

as a replacement fuel for coal. Co-combustion of sewage sludge together with coal or wood has been investigated in two circulating fluidized bed (CFB) plants by Leckner et al. (2004). The investigation focused on the emission of harmful gases from co-combustion compared to mono-combustion in CFB and the influence of air supply. The result showed that co-combustion can be carried out in CFB plant designed for the base fuel without exceeding allowable limits for sludge energy fractions of less than 25%, except for the chlorine emission that may have to be reduced by flue gas treatment. Although sewage sludge contains large quantities of nitrogen and sulfur, the beneficial properties of CFB lead to considerable reduction of nitrogen oxides, and only a few percent of the nitrogen was effectively converted to NO or N₂O. Sulfur can be captured by conventional limestone addition, when coal is the base fuel. This method is not as efficient if wood is the base fuel. Zabaniotou and Theofilou (2008) and Chiou et al. (2006) reported from the co-combustion of biosolids in cement kilns that heavy metal emissions were 16% of the allowable levels and total dioxins and furans were only 6% of allowable levels of EU legislation. Poletschny (1988), Dangtran et al. (2000) and Chiou et al. (2006) reported emissions from biosolids incineration and heavy metals in typical sludges and sludge ash. Most of the emissions are below the permissible US EPA limit, but PM is higher than allowable limits in some cases.

3.4. Greenhouse gas emissions from biosolids incineration

Carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are important greenhouse gases (GHGs) related to biosolids management. The understanding of these three GHGs is inversely related to the relative importance of the GHGs; N₂O and CH₄ are

298 and 25 times more potent GHGs than CO₂ respectively for 100-year time horizon (IPCC/TEAP, 2005). Table 4 shows rates of N₂O emissions from different types of combusted biosolids and Table 5 shows tonne CO₂ equivalents from different biosolid management scenarios across Canada (Ned et al., 2009). Incineration scenario shows high levels of tonne CO₂ eq/tonne dry solids. However, the estimated emissions of N₂O are responsible for 99.3% of the total estimated GHG emissions. Depending on the mean temperature, biosolid combustion can create significant quantities of N₂O, which has the highest global warming potential. If this combustion temperature is above 900 °C however, N₂O emissions are likely to be minimal (Ned et al., 2009).

4. Materials and methods

4.1. Biosolids

The remainder of this paper presents a description of biosolids used in this study and the results of combustion and emission tests performed using a conventional wood stove. This study used biosolids as a fuel for co-combustion with biomass fuels. N-Viro systems Canada LP supplied the biosolids. The following is a short description of biosolids process.

The process involves mixing sewage sludge with an alkaline admixture, principally kiln dust and fly ash, and then subjecting the mixture to a controlled period of storage and mechanical turning and drying, as illustrated in Fig. 1. The sewage sludge is mechanically dewatered. Alkaline admixtures (AA), usually industrial by-products such as cement kiln dust, lime-kiln dust, fly ash and/or steel-making fines supplemented in some cases with quicklime, are then mixed with the dewatered sludge. The admixtures are dosed at a rate of 20–60% of the wet-weight sludge depending on the amount of heating required, the type of sludge (the higher the solids content the lower the AA dosage) and the characteristics of the alkaline admixture.

Following the combination of alkaline admixture with the sludge, the mixture is placed in a pile and heated by the exothermic chemical reaction (the 'Heat Pulse') between the sludge and the alkaline admixture. A minimum temperature of 52 °C is maintained for at least 12 h and the pH of the mixture is maintained above 12 for at least 72 h. After maintaining the required temperature for 12 h, the mixture typically is laid out uncovered in

Table 5
Summary of GHG emissions from the biosolids management scenarios (Ned et al., 2009).

Biosolids management scenario	Jurisdiction	Population served	Wastewater treated (million L/day)	Net GHG emissions (tonne CO ₂ eq/year)	GHG emissions (tonne CO ₂ eq/tonne dry solids)
1	Thunder Bay	100,000	70	1462	0.09
2	City X	330,000	295	19,608	1.63
3	Laval	271,633	254	10,277	1.02
4	Windsor	181,348	161	2427	0.22
5	Moncton	125,000	79	1123	0.18
6	Vancouver	980,000	436	–1868	–0.16
7	Halifax	54,000	27	–875	–0.15
8	Nanaimo	25,000	10	177	0.11
9	Halton	165,000	96	–531	–0.18

Scenario description:

1. Anaerobically digested, dewatered biosolids mixed with native topsoil and applied as cover on a landfill;
2. Incineration of dewatered sludge and use of incinerator ash in cement production;
3. High temperature drying of dewatered, undigested sludge, followed by incineration at a cement kiln and landfilling primary sludge;
4. High temperature drying/pelletization and land application;
5. Composting of alkaline stabilized, dewatered biosolids;
6. Application of dewatered, anaerobically digested biosolids to disturbed land, and anaerobic digester gas utilization to produce electricity;
7. Agricultural land application of alkaline stabilized, dewatered biosolids and anaerobic digester gas utilization to produce heat;
8. Land application of dewatered, aerobically digested biosolids; and
9. Agricultural land application of liquid and dewatered anaerobically digested biosolids.

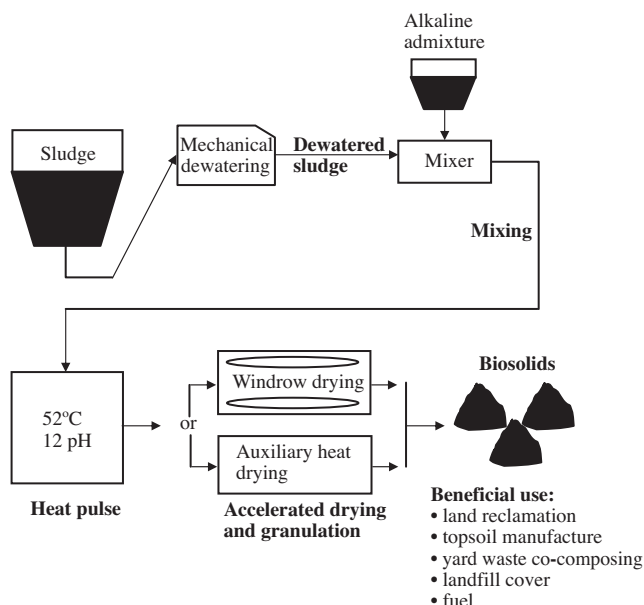


Fig. 1. Biosolids process.

windrows approximately four to six feet high and ten to twelve feet wide. During this time, the pH of the mixture is maintained above 12 for at least an additional 60 h. The process is regulated under 40 CFR Part 503 rules as alternative 2 (temperature > 52 °C for 12 h, pH > 12 for 72 h, and solids > 50%). Windrows are intermittently turned to promote drying, increase granulation and prevent compaction until the solids content reaches and maintains a minimum of 50%. When these criteria are met, the product satisfies EPA standards. This biosolid is used as the fuel for co-combustion with biomass pellets for this study.

Initial experiments involved laboratory analysis of fuel characteristics through proximate analysis, ultimate analysis and higher heating value determination of different fuels. After fuel characterization, the biosolid was tested in a small wood pellet stove for combustion and emission analysis. Biosolids were co-fired with wood pellet up to a maximum ratio of 50%.

The different data samples were obtained thrice for each test point with the exception of ultimate analysis, where two data samples were taken. The average of data set is shown in the tables. Similar conditions were maintained for all tests to allow a better comparison of the results. The standard deviations of important performance and emission parameters are: 0.55% for overall efficiency, 4.32 ppm for CO, 1.4 ppm for NO_x and 0.8 ppm for SO₂.

4.2. Experimental apparatus and test procedure

A DROLET freestanding wood pellet stove (Eco-35) with 2.4–10.25 kW output capacity was used to perform the combustion experiments. The fuel source consisted of premium wood pellets and biosolids–wood pellet combinations. The stove is comprised of: (1) a hopper, (2) an auger with auger motor, (3) a burn pot, (4) a control board (touch screen), (5) a full size ash drawer, (6) A cleaning access panel, (7) fresh air intake, (8) air supply control, (9) igniter, (10) convection and exhaust blowers and (11) thermistors and switches. The specifications of Eco-35 stove are presented in Table 6.

4.3. Thermal analysis of combustion

The purpose of thermal analysis of combustion is to determine the overall efficiency and different losses. Basically efficiency can

Table 6
Specifications of Eco-35 stove.

Parameters	Unit	System/values
Heat output	kW	2.4–10.25
Hopper capacity	kg	16
Burn rate	kg/h	0.59–2.04, six heat settings
Ignition system	–	Electronic
Maximum recommended heating area	sq. m	150
Exterior dimensions	cm × cm × cm	56.52 W × 63.98 D × 72.39 H
Approved vent diameter	cm	7.62–10.16
Electrical requirement	–	120 VAC–60 Hz–15 A
Type of door	–	Glass with cast iron frame
Glass type	–	Ceramic glass
Glass surface	sq. cm	664.5
Weight	kg	86.18

be tested by the direct method where the energy gain of the working fluid is compared with the energy content of the fuel, and by the indirect method where the efficiency is the difference between the losses and the energy input. This study used the indirect method to calculate overall efficiency. The following are the pertinent losses.

- (1) % Heat loss due to dry flue gas (dry flue loss) = $m_{\text{dry}} \times C_p \times (T_g - T_a) \times 100/\text{HHV}$; where m_{dry} is the mass of dry flue gas in kg/kg of fuel, C_p is specific heat of flue gas in kcal/kg °C, T_g is flue gas temperature in °C, T_a is ambient air temperature in °C and HHV is higher heating value in kcal/kg.
- (2) % Heat loss due to wet flue gas (wet loss) = $(m_{\text{moisture}} \times (h_g \text{ at } T_g - h_f \text{ at ambient temperature})) \times 100/\text{HHV}$; where m_{moisture} is the sum of water vapor produced from hydrogen in fuel, moisture present in fuel and moisture present in air in kg/kg of fuel, h_g is enthalpy of steam at the temperature T_g in kcal/kg and h_f is enthalpy of water at ambient temperature in kcal/kg.
- (3) % Heat loss due to partial conversion of C to CO (CO loss) = $[\% \text{CO} \times C/(\% \text{CO} + \% \text{CO}_2)] \times [5744/\text{HHV}] \times 100$; where 5744 is heat loss (in kcal) due to partial combustion of carbon (C). C is carbon content in kg/kg of fuel; HHV is in kcal/kg.
- (4) Radiation and unaccounted loss. This is taken as 2% (ABMA chart and experience).

Overall efficiency by indirect method = 100 – (sum of losses).

Theoretical (stoichiometric) air fuel ratio and excess air supplied were determined first for computing the losses. Theoretical air required for combustion is determined from stoichiometric calculation with fuels ultimate/proximate analysis data. Excess air supplied is measured from flue gas analysis. Dry flue gas loss is the greatest loss and can be calculated from mass of dry flue gas, specific heat of flue gas, and the difference between flue gas temperature and ambient temperature. Wet flue gas loss is the second largest loss. Water vapor is produced from hydrogen in fuel, moisture present in fuel and air during the combustion. The losses due to these components are separately calculated and their sum is taken as a wet flue gas loss. Loss due to CO production is also calculated. The share of CO in flue gas loss is very small in most of the cases. However, with 50% wood pellet and 50% biosolids CO loss is 1.59%. A typical radiation and unaccounted loss of 2% is assumed. It should be noted that presently so called combustion efficiency of the boiler is determined by flue gas analyzer by Atkins et al. (2010) and Gonzalez et al. (2004). This does not give the actual overall efficiency of the system. Gas analyzer only accounts dry flue gas loss using Siegert's formula. The Siegert's formula is

Table 7

Ultimate analysis, proximate analysis and the higher heating value (HHV) of sewage sludge, biosolids and wood pellets.

Analysis	Different fuels		
	Sewage sludge	Biosolids	Wood pellet
<i>Ultimate analysis, db (%)</i>			
Carbon	16.36	13.82	48.75
Hydrogen	6.25	2.28	6.54
Nitrogen	0.97	0.74	0.05
Sulfur	0.33	0.94	0.24
Oxygen (by difference)	60.82	29.38	44.10
<i>Proximate analysis (%)</i>			
Moisture (as received)	71.25	29.35	5.00
Ash (db)	15.27	52.84	0.32
Volatile matter (db)	78.33	45.44	89.80
Fixed carbon (db)	6.40	1.73	9.88
HHV, as received (kcal/kg)	1329	808	4516

db: Dry basis and HHV: higher heating value.

$$S_L = (T_{\text{gas}} - T_{\text{amb}}) \cdot \left(\frac{A1}{CO_2} + B \right)$$

where S_L – chimney loss – the percentage of heat produced in combustion process which is convected with the combustion gases; T_{gas} – flue gas temperature; T_{amb} – the temperature of the boiler inlet air (it is assumed by the analyzer to be the ambient temperature); CO_2 – the calculated (on the basis of oxygen concentration and $CO_{2\text{max}}$) amount of CO_2 in combustion gases, expressed in [vol.%]; $A1$, B – factors characteristic for a given fuel type.

Based on the calculated chimney loss the analyzer estimates the efficiency of the combustion process η

$$\eta = 100\% - S_L$$

where η – combustion efficiency.

Wet flue gas loss is a significant loss in case of biomass combustion. Atkins et al. (2010) has shown efficiency greater than 82% and Gonzalez et al. (2004) greater than 91%. This study presents actual overall efficiency considering all losses.

4.4. Emission measurements

After achieving steady state operation with stable flue temperatures, gas emissions were measured using a Unigas 3000⁺ flue gas analyzer. In gas composition O_2 , CO_2 , CO , NO , NO_x and SO_2 were measured. The measurement principles of the gas analyzers are electrochemical for O_2 , CO , NO , NO_2 and SO_2 , and calculated for CO_2 and NO_x .

5. Results and discussion

At a constant fuel flow rate (1.2 kg/h), the performance was tested under steady state condition. Steady state was considered when there was almost no change or fluctuation in flue gas temperatures and emission parameters. It took almost 30 min to reach steady state condition. Table 7 shows the results of fuel characterization (proximate and ultimate analysis and higher heating value). It can be seen from Table 7 that biosolids have the lowest heating value (approximately 20% of wood pellets) due to higher ash and moisture content. Therefore, no sustainable combustion was possible using biosolids only. More than 50% of biosolid material, however is ash; this ash content can be reduced by adding lime (calcium oxide, CaO) with biosolids instead of cement kiln dust (CKD) as an alkaline admixture, as lime has higher pH value than CKD. Saturated lime has a pH value of 12.4, whereas calcium carbonate, the largest share in CKD has a pH of 9.4 (Adaska and Taubert, 2008). Here, cost might be a concern that needs to be considered.

Tables 8 and 9 show combustion and emission data for different fuels. It was found that co-firing 5% biosolids with 95% wood pellets produced very similar overall efficiency and CO emissions 22% lower than 100% wood pellets. NO_x emission increased from 18 ppm for 100% wood pellets to 25 ppm for 5–95% biosolids–wood pellet combination. Wood pellets did not produce any SO_2 , whereas 5–95% biosolids–wood pellet combination produced only 2 ppm of SO_2 . With 10–90% biosolids–wood pellet combination, overall efficiency decreased by only 1.4%, but CO decreased by 25% of that found with wood pellets. NO_x emission increased to 30 ppm, but SO_2 is still at 2 ppm level with 10–90% biosolids–wood pellet combination. A combination of 20% biosolids and 80% wood pellets and 50% biosolids and 50% wood pellets showed a significant degradation of efficiency and emissions. The decrease in efficiency was over 4% and 11% for 20% and 50% biosolids, respectively. The lowest CO of 135 ppm for 10–90% biosolids–wood pellet combination and the highest CO of 703 ppm for 50–50% biosolids–wood pellets were observed. The decrease in CO emissions for 10–90% biosolids–wood pellet combination is thought to be due to the lower carbon content of biosolids (biosolids contains only 28% C of wood pellet) maintaining good combustion, whereas the highest CO for 50–50% biosolids–wood pellets is due to inefficient combustion due to high moisture and ash content as well as very low heating value of the tested biosolids, for which the flame temperature became low. However, higher NO_x was produced with a higher percentage of biosolids in the fuel mixture. This is thought to be due to higher N_2 content of biosolids.

Table 8

Overall efficiency and losses for different fuels.

Fuel type	Overall eff. (%)	Dry flue loss (%)	Wet gas loss (%)	CO loss (%)	Radiation and unaccounted loss (%)	Total loss (%)
Premium wood pellet	62.24	23.00	12.35	0.41	2	37.76
Biosolids 5% + pellet 95%	61.84	23.30	12.54	0.32	2	38.16
Biosolids 10% + pellet 90%	61.36	23.43	12.90	0.31	2	38.64
Biosolids 20% + pellet 80%	59.66	23.67	14.11	0.56	2	40.34
Biosolids 50% + pellet 50%	54.17	24.40	17.84	1.59	2	45.83

Table 9

Emissions and temperatures for different fuels.

Fuel type	O_2 (%)	CO_2 (%)	Flue temp. (°C)	Ambient temp. (°C)	CO (ppm)	NO_x (ppm)	SO_2 (ppm)
Premium wood pellet	16.2	4.8	190	20	181	18	0
Biosolids 5% + pellet 95%	16.3	4.7	188	20	141	25	2
Biosolids 10% + pellet 90%	16.5	4.5	186	20	135	30	2
Biosolids 20% + pellet 80%	16.8	4.2	167	20	247	40	2
Biosolids 50% + pellet 50%	18.3	2.7	126	20	703	57	3

The three main reasons for NO_x formation during biomass combustion reported by Habi et al. (2008), Werther et al. (2000), Nussbaumer and Hustad (1997) and De Soete (1990) are: thermal NO_x (formed from atmospheric nitrogen, above 1300 °C), the prompt NO_x (formed at the flame front) and the fuel-NO_x (formed from elemental nitrogen contents of the fuel). However, at temperatures below 1300 °C only fuel-NO_x is expected (Werther et al., 2000; De Soete, 1990) which is usually the case for small domestic stoves. Therefore, the lowest NO_x emissions from wood pellets and the highest NO_x emissions in the case of 50–50% biosolids–wood pellets were probably a consequence of the smallest and largest elemental nitrogen content of these fuels, respectively. Ash production increased with an increase in biosolids in the fuel mixture, for example ash is increased from 0.3% for wood pellets to 4% for a 10% biosolids to 90% pellet ratio, where the efficiency decrease was only 1.4%.

6. Conclusions

This study presents a short review on biosolids management and the results of a project to investigate the potential use of biosolids as a partial substitute for wood pellets in combustion facilities. The results include energy values, efficiency and emissions obtained from laboratory analysis and combustion tests performed on a wood pellet stove. The following conclusions can be drawn from the literature review and experimental works regarding biosolids management.

- (1) Thermal treatment of biosolids is attractive both for volume reduction and energy recovery and will play an important role in biosolids management in the future as technology advances and conversion efficiencies improve. Among thermal treatment methods, incineration/co-combustion has great potential to be used effectively and in large scale in the near future.
- (2) Sewage sludge could be a potential fuel if the moisture content can be removed economically. Drying by exhaust heat could be a potential and economically feasible option.
- (3) Biosolids contain higher nitrogen and sulfur producing higher NO_x and SO_x. Although NO_x production is less and SO₂ is negligible, co-combustion of biosolids with wood pellets might be helpful in reducing NO_x and SO_x in high temperature combustion as wood pellet contains less nitrogen and sulfur.
- (4) The biosolids tested in this study cannot provide self-sustained combustion in its present form due to its low heating value and high moisture and ash content. However, co-combustion of a small portion of biosolids with wood pellets showed great potential in terms of combustion efficiency and gas emissions. Biosolids up to 10% mixed with wood pellets can be burned without any significant degradation of efficiency and emissions. However, it is recommended to conduct further detailed tests to evaluate emissions such as PM, dioxin, furan and PAH.

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